

MEMS: Mega promise for micro devices

Industrial and commercial applications of micro electrical mechanical systems (MEMS) are growing exponentially. Some industry insiders are hailing MEMS as a breakthrough that could prove to be as revolutionary to modern technology as the integrated circuit.

Ranked among the top ten technologies by the Department of Defense's Advanced Research Projects Agency (ARPA), which provides significant funding for MEMS-related research, MEMS are broadly defined as miniature mechanical devices created from silicon using photolithographic micromachining techniques. The devices integrate microscopic mechanical moving structures and integrated circuits, often on the surface of a single chip. In addition to sensing and measuring force, motion, light, electromagnetism, and chemicals, their computer circuitry enables them to make decisions and act on the information received.

MEMS technology was first developed in the 1960s to make pressure sensors for aerospace and industrial applications, but its popularity exploded in the early 1980s with the emergence of two high-volume applications: automotive pressure sensors for pollution control, and disposable blood pressure sensors. About the same time, researchers began to explore the possibility of using MEMS for microrelays, display devices, and accelerometers used in automobile air-bag deployment systems, which is currently one of the biggest markets for MEMS technology.

A Pentagon assessment last year estimated that the total MEMS market could reach \$8 billion by the end of this century, while other analysts predict it could reach \$14 billion. In 1994 alone, automobile manufacturers installed nearly 5 million microaccelerometers

for airbag deployment. More than 17 million miniature pressure sensors were made and sold for automotive and biomedical uses, and 20 million disposable blood pressure sensors are used annually in the United States. MEMS devices are also finding applications in the ink jets of many computer printers.

Ten years ago, only a handful of Fortune 500 companies were working on microma-

chining, compared to some 20 to 30 companies today that are investing heavily in MEMS technology. Virtually every technical department in every major university now has a micromachining program. Start-up companies devoted to MEMS are also emerging, such as Lucas Novasensor (Fremont, California), which specializes in pressure and acceleration sensors for the automotive industry, and the fledgling Sepheid (San Jose, California), which plans to use MEMS for microfluidic applications, particularly the new generation of handheld biomedical testing equipment.

accelerometers used for airbag deployment crash sensors, vehicle dynamics, and auto security applications by such major vehicle manufacturers as General Motors (Detroit, Michigan) and Honda (Torrance, California). ADI has seen a tremendous increase in demand for its products. In February it announced the establishment of a new fabrication facility, which will allow the company to pursue other attractive market opportunities, including tilt sensing, vibration sensing, military applications, and virtual reality. The plant is expected to be fully operational by the third quarter of 1997.

Applications

In addition to the established markets for MEMS, several promising new applications are beginning to emerge. Integrated Micromachines, Inc. (IMMI), San Marino, California, seeks to commercialize a product family of ultraminiaturized electromagnetic silicon microrelays and microswitches for high-technology industrial applications, beginning with the \$3.4 billion semiconductor automatic test equipment (ATE) industry. IMMI President Denny K. Miu estimates the replacement market for ATE

microrelays at \$20 million today, expected to exceed \$60 million over the next five years.

Miu also sees considerable growth potential for integrated microrelays in telecommunications and data communication switching. "It was once thought that solid state technology would eventually replace electromechanical relays," said Miu. "What has happened is actually the opposite. Electronics are stimulating growth for relays instead of displacing them." Solid-state relays currently account for less than 12% of the worldwide relay market, which in 1995 was about \$2.5 billion. Hughes Aircraft Co. (El Segundo, California), Rockwell International (Newport Beach, California), and Texas



A wobble micromotor fabricated in a single crystal of silicon using a process combining deep reactive ion etching and wafer level silicon fusion bonding (Lucas Novasensor).

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Analog Devices, Inc. (ADI) in Norwood, Massachusetts, is a leader in micromachined

Instruments (Dallas, Texas) are also among those investing in micromachined microwave switches for cellular telephones.

Texas Instruments is making flat-panel displays using micromachined elements. Data storage is another area where MEMS are expected to have a big impact. "Computer displays, instruments, and storage devices are still shrinking dramatically, but the next generation of mechanical storage devices are going to have to be so much smaller that we won't be able to accomplish it by conventional mechanical techniques," said Kurt Petersen, co-founder of both Sepheid and Lucas Novasensor.

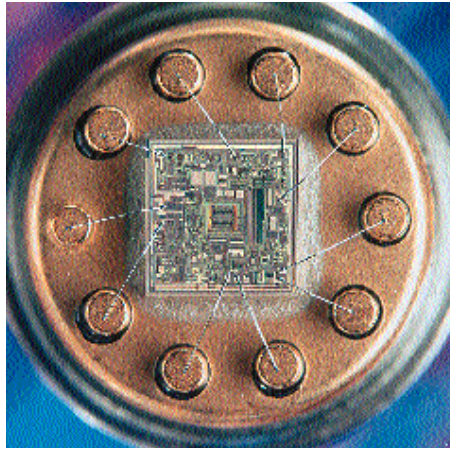
Scientists at the University of California, Berkeley, demonstrated the first micromotor in 1989, measuring a mere $100\ \mu\text{m}$ in diameter, but few practical applications have emerged to date. The most promising area for micromotors is optics, according to Petersen. For example, a UCLA group is making miniature optical benches on a single chip. Another group at Sandia National Labs is investigating the possibility of using micromotors in the fuses that determine whether to arm a nuclear warhead, and it is possible linear micromotors might eventually be used to move writing elements across data storage media.

While the focus to date has been on single MEMS devices, the market is moving toward large arrays or networks of MEMS sensors. This is expected to open up even more applications, especially as the devices become cheaper to manufacture. "Sensors and small actuators can creep into every possible design if they can be made cheap and robust enough, and the fact that they're made with microfabrication means that the potential for low cost is always there," said John Gilbert, chief technical officer at the Cambridge, Massachusetts office of Microcosm Technologies, Inc. "If you want a sensor and it can be done with MEMS, you can get to low cost if your volume is high enough." The demand for MEMS in the automotive sensor market alone has driven the cost down to \$5 per chip.

Microinstrumentation

A transition from microsensors to microinstrumentation is also under way. Researchers such as Alan Feinerman of the University of Illinois, Chicago (UIC) are now using special fabrication techniques, such as selective anodic bonding and stacking silicon chips with pyrex fibers, to integrate charged particle sources, electrodes and detectors into various miniature instruments. For example, Feinerman is developing a miniature scanning electron microscope the size of a sugar cube, which could eventually be used in conjunction with atomic force microscopes to help pinpoint one's location on a sample with a resolution of $1\ \mu\text{m}$.

Scientists at Argonne National Laboratory are working on a miniature mass spectrometer, and a miniature linear accelerator to produce hard X-rays of intermediate intensity to complement its Advanced Proton Source. UIC's Gary Friedman is developing micro-NMR instruments to detect small impurities in liquids. "Analytical instruments of this size will allow the laboratory to be brought to the



Low gravity surface micromachined accelerometer with signal conditioning on chip (Analog Devices, Inc.).

sample, which will be essential when the sample must be observed in situ," said Feinerman, citing toxic waste sites as an example.

Perkin-Elmer Corporation (Norwalk, Connecticut) is working on applying MEMS technology to the tabletop instruments used in DNA sequencing and analysis, as is M. Allen Northrup, a chemist at Lawrence Berkeley National Laboratory. The current machines cost between \$7,600 and \$14,000 each and

require 90 minutes to run a test, compared to the \$85 price tag of Northrup's prototype, which is said to require only 20 minutes to complete tests.

Other applications conceived by scientists are a little farther off in the future. For instance, Japanese researchers are creating tweezers and other surgical tools small enough to be threaded into the brain to repair life-threatening defects in blood vessels. Military researchers are developing microgyroscopes to accurately guide common tank shells to their targets, similar to the electronics in today's guided missiles.

Design software

A strong related market is emerging in MEMS design software. In addition to developing micromachined sensors, Intellisense Corporation (Wilmington, Massachusetts) is a world leader in the development and commercialization of CAD software for MEMS design and manufacturing. Microcosm offers a suite of software tools called MEMCAD, which allows designers to develop, model,

and analyze MEMS devices in a three-dimensional environment. The core technology was originally developed by and licensed from MIT scientists, including MIT's Stephen Senturia, who believes that the future of the field depends on the widespread availability of robust and versatile CAD tools.

According to Michael Jamiolkowski, president of Microcosm, MEMCAD integrates tools in a single seamless environment, unlike the more fragmented software tools of the past, making it one of the most advanced and promising CAD tools for the next generation of MEMS applications. "It's a much bigger market than device creation. People don't just want to design the device itself, they want to be able to simulate the device within a system, whether it be electrical, mechanical, or optical," he said. "They need MEMS software to be able to analyze the functionality of the device, as well as see how well it performs and interacts with the environment."

In March, Microcosm announced partnership contracts with both Ford Microelectronics, Inc. (Colorado Springs, Colorado) and Texas Instruments. Ford will use Microcosm software for the design and analysis of MEMS devices for automotive applications. Texas Instruments plans to use the software to model such MEMS devices as spatial light modulators, optical switches, and sensors. Microcosm will add system-level technology later this year for higher-level modeling of MEMS devices with their electronic counterparts.

Future challenges

Despite the explosion of research and potential applications, there are some who take a more cautious view of the market potential for MEMS. Fariborz Maseeh, president of Intellisense, points out that while demand is strong, much of the growth in the MEMS industry is in new markets; the devices have thus far failed to make inroads into key replacement markets. He pegs the total market potential for MEMS in the multibillion-dollar U.S. sensor industry

alone at \$700–\$800 million this year.

"MEMS are cheaper, but do not necessarily perform better, and we still don't know how to manufacture these devices well enough to compete with the performance of more large-scale devices," said Maseeh, adding that unless cost and size are the key manufacturing issues in a specific market, more traditional technologies will win out. While MEMS are fairly simple to manufacture in a university laboratory, it is difficult to mass-produce the devices, and even more difficult to persuade commercial companies to use such new technologies in their high-volume applications.

"The MEMS market has probably been overplayed to some extent," agreed Gilbert. "The potential market is clearly there, but there's been a lot of press that says they're going to revolutionize the universe, and things that revolutionize the universe invariably do so at a pace that is dramatically slower than what people originally expected."

Nevertheless, the huge demand for MEMS is translating into a corresponding need for workers with experience in commercializing the devices. While engineers are the hottest employment commodity, physicists are needed to improve our understanding of the role of surfaces within ultrasmall devices. "The dimensions of these devices are so small that the conventional mechanical analysis techniques and typical phenomena that occur are quite different at these microscales," said Petersen, citing static friction and charging effects as two examples.

ADI's Richard Payne, a liquid helium physicist who migrated into semiconductors 20 years ago, sees opportunities for physicists in materials processing and circuit design, as well as fabrication techniques. Gilbert, another Ph.D. physicist, believes the interdisciplinary nature of the field makes it well suited for those with physics backgrounds. "MEMS are all about transduction, either for sensors or for actuators, and that means converting from one physical domain to another," he said. "That alone should make it interesting for physicists." 